NIST NCSTAR 1
Federal Building and Fire Safety Investigation
of the World Trade Center Disaster

Final Report on the Collapse of the World Trade Center Towers

NIST
National Institute of
Standards and Technology
Technology Administration
U.S. Department of Commerce

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September 2005

U.S. Department of Commerce
Carlos M. Gutierrez, Secretary

Technology Administration
Michelle O'Neill, Acting Under Secretary for Technology

National Institute of Standards and Technology
William Jeffrey, Director

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DEDICATION

On the morning of September 11, 2001, Americans and people around the world were shocked by the destruction of the World Trade Center (WTC) in New York City and the devastation of the Pentagon near Washington, D.C., after large aircraft were flown into the buildings, and the crash of an aircraft in a Pennsylvania field that averted further tragedy. Four years later, the world has been changed irrevocably by those terrorist attacks. For some, the absence of people close to them is a constant reminder of the unpredictability of life and death. For millions of others, the continuing threats of further terrorist attacks affect how we go about our daily lives and the attention we must give to homeland security and emergency preparedness.

Within the construction, building, and public safety communities, there arose a question pressing to be answered: How can we reduce our vulnerability to such attacks, and how can we increase our preparedness and safety while still ensuring the functionality of the places in which we work and live?

This Investigation has, to the best extent possible, reconstructed the response of the WTC towers and the people on site to the consequence of the aircraft impacts. It provides improved understanding to the professional communities and building occupants whose action is needed and to those most deeply affected by the events of that morning. In this spirit, this report is dedicated to those lost in the disaster, to those who have borne the burden to date, and to those who will carry it forward to improve the safety of buildings.

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ABSTRACT

This is the final report on the National Institute of Standards and Technology (NIST) investigation of the collapse of the World Trade Center (WTC) towers, conducted under the National Construction Safety Team Act. This report describes how the aircraft impacts and subsequent fires led to the collapse of the towers after terrorists flew jet fuel laden commercial airliners into the buildings; whether the fatalities were low or high, including an evaluation of the building evacuation and emergency response procedures; what procedures and practices were used in the design, construction, operation, and maintenance of the towers; and areas in current building and fire codes, standards, and practices that warrant revision. Extensive details are found in the 42 companion reports. The final report on the collapse of WTC 7 will appear in a separate report.

Also in this report is a description of how NIST reached its conclusions. NIST complemented in-house expertise with private sector technical experts; accumulated copious documents, photographs, and videos of the disaster; established baseline performance of the WTC towers; performed computer simulations of the behavior of each tower on September 11, 2001; combined the knowledge gained into a probable collapse sequence for each tower; conducted nearly 1,200 first-person interviews of building occupants and emergency responders; and analyzed the evacuation and emergency response operations in the two high-rise buildings.

The report concludes with a list of 30 recommendations for action in the areas of increased structural integrity, enhanced fire endurance of structures, new methods for fire resistant design of structures, enhanced active fire protection, improved building evacuation, improved emergency response, improved procedures and practices, and education and training.

Keywords: Aircraft impact, building evacuation, emergency response, fire safety, human behavior, structural collapse, tall buildings, wind engineering, World Trade Center.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

Acronyms

AA	American Airlines
ARA	Application Research Associates
ASTM	ASTM International
BOCA	Building Officials and Code Administrators
BPS	Building Performance Study
FCD	Fire Command Desk
FDNY	The Fire Department of the City of New York
FDS	Fire Dynamics Simulator
FEMA	Federal Emergency Management Agency
FSI	Fire Structure Interface
IBC	International Building Code
LERA	Leslie E. Robertson Associates
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NYC	New York City
NYPD	New York City Police Department
NYS	New York State
PANYNJ	The Port Authority of New York and New Jersey
PAPD	Port Authority Police Department
SFRM	sprayed fire-resistive material
SGH	Simpson Gumpertz & Heger, Inc.
SOM	Skidmore, Owings and Merrill
UA	United Airlines
USC	United States Code
WSHJ	Worthington, Skilling, Helle and Jackson
WTC	World Trade Center
WTC 1	World Trade Center 1 (North Tower)

WTC 2	World Trade Center 2 (South Tower)
WTC 7	World Trade Center 7

Abbreviations and Conversion Factors

°C	degrees Celsius	T (°C) = 5/9 [T (°F) – 32]
°F	degrees Fahrenheit	
ft	feet	
gal	gallon	1 gal = 3.78×10^{-3} m^3
GJ	gigajoule	
GW	gigawatt	
in.	inch	
kg	kilogram	
kip	1,000 lb	
ksi	1,000 $lb/in.^2$	
lb	pound	1 lb = 0.453 kg
m	meter	1 m = 3.28 ft
µm	micrometer	
min	minute	
MJ	megajoule	
MW	megawatt	
psi	pounds per square inch	
s	second	
T	temperature	

PREFACE

Genesis of This Investigation

Immediately following the terrorist attack on the World Trade Center (WTC) on September 11, 2001, the Federal Emergency Management Agency (FEMA) and the American Society of Civil Engineers began planning a building performance study of the disaster. The week of October 7, as soon as the rescue and search efforts ceased, the Building Performance Study Team went to the site and began its assessment. This was to be a brief effort, as the study team consisted of experts who largely volunteered their time away from their other professional commitments. The Building Performance Study Team issued its report in May 2002, fulfilling its goal "to determine probable failure mechanisms and to identify areas of future investigation that could lead to practical measures for improving the damage resistance of buildings against such unforeseen events."

On August 21, 2002, with funding from the U.S. Congress through FEMA, the National Institute of Standards and Technology (NIST) announced its building and fire safety investigation of the WTC disaster. On October 1, 2002, the National Construction Safety Team Act (Public Law 107-231), was signed into law. (A copy of the Public Law is included in Appendix A). The NIST WTC Investigation was conducted under the authority of the National Construction Safety Team Act.

The goals of the investigation of the WTC disaster were:

- To investigate the building construction, the materials used, and the technical conditions that contributed to the outcome of the WTC disaster.
- To serve as the basis for:
  - Improvements in the way buildings are designed, constructed, maintained, and used;
  - Improved tools and guidance for industry and safety officials;
  - Recommended revisions to current codes, standards, and practices; and
  - Improved public safety.

The specific objectives were:

1. Determine why and how WTC 1 and WTC 2 collapsed following the initial impacts of the aircraft and why and how WTC 7 collapsed;
2. Determine why the injuries and fatalities were so high or low depending on location, including all technical aspects of fire protection, occupant behavior, evacuation, and emergency response;
3. Determine what procedures and practices were used in the design, construction, operation, and maintenance of WTC 1, 2, and 7; and
4. Identify, as specifically as possible, areas in current building and fire codes, standards, and practices that warrant revision.

NIST is a nonregulatory agency of the U.S. Department of Commerce's Technology Administration. The purpose of NIST investigations is to improve the safety and structural integrity of buildings in the United States, and the focus is on fact finding. NIST investigative teams are authorized to assess building performance and emergency response and evacuation procedures in the wake of any building failure that has resulted in substantial loss of life or that posed significant potential of substantial loss of life. NIST does not have the statutory authority to make findings of fault nor negligence by individuals or organizations. Further, no part of any report resulting from a NIST investigation into a building failure or from an investigation under the National Construction Safety Team Act may be used in any suit or action for damages arising out of any matter mentioned in such report (15 USC 281a, as amended by Public Law 107-231).

Organization of the Investigation

The National Construction Safety Team for this Investigation, appointed by the then NIST Director, Dr. Arden L. Bement, Jr., was led by Dr. S. Shyam Sunder. Dr. William L. Grosshandler served as Associate Lead Investigator, Mr. Stephen A. Cauffman served as Program Manager for Administration, and Mr. Harold E. Nelson served on the team as a private sector expert. The Investigation included eight interdependent projects whose leaders comprised the remainder of the team. A detailed description of each of these eight projects is available at http://wtc.nist.gov. The purpose of each project is summarized in Table P–1, and the key interdependencies among the projects are illustrated in Fig. P–1.

Table P–1. Federal building and fire safety investigation of the WTC disaster.

Technical Area and Project Leader	Project Purpose
Analysis of Building and Fire Codes and Practices; Project Leaders: Dr. H. S. Lew and Mr. Richard W. Bukowski	Document and analyze the code provisions, procedures, and practices used in the design, construction, operation, and maintenance of the structural, passive fire protection, and emergency access and evacuation systems of WTC 1, 2, and 7.
Baseline Structural Performance and Aircraft Impact Damage Analysis; Project Leader: Dr. Fahim H. Sadek	Analyze the baseline performance of WTC 1 and WTC 2 under design, service, and abnormal loads, and aircraft impact damage on the structural, fire protection, and egress systems.
Mechanical and Metallurgical Analysis of Structural Steel; Project Leader: Dr. Frank W. Gayle	Determine and analyze the mechanical and metallurgical properties and quality of steel, weldments, and connections from steel recovered from WTC 1, 2, and 7.
Investigation of Active Fire Protection Systems; Project Leader: Dr. David D. Evans; Dr. William Grosshandler	Investigate the performance of the active fire protection systems in WTC 1, 2, and 7 and their role in fire control, emergency response, and fate of occupants and responders.
Reconstruction of Thermal and Tenability Environment; Project Leader: Dr. Richard G. Gann	Reconstruct the time-evolving temperature, thermal environment, and smoke movement in WTC 1, 2, and 7 for use in evaluating the structural performance of the buildings and behavior and fate of occupants and responders.
Structural Fire Response and Collapse Analysis; Project Leaders: Dr. John L. Gross and Dr. Therese P. McAllister	Analyze the response of the WTC towers to fires with and without aircraft damage, the response of WTC 7 in fires, the performance of composite steel-trussed floor systems, and determine the most probable structural collapse sequence for WTC 1, 2, and 7.
Occupant Behavior, Egress, and Emergency Communications; Project Leader: Mr. Jason D. Averill	Analyze the behavior and fate of occupants and responders, both those who survived and those who did not, and the performance of the evacuation system.
Emergency Response Technologies and Guidelines; Project Leader: Mr. J. Randall Lawson	Document the activities of the emergency responders from the time of the terrorist attacks on WTC 1 and WTC 2 until the collapse of WTC 7, including practices followed and technologies used.

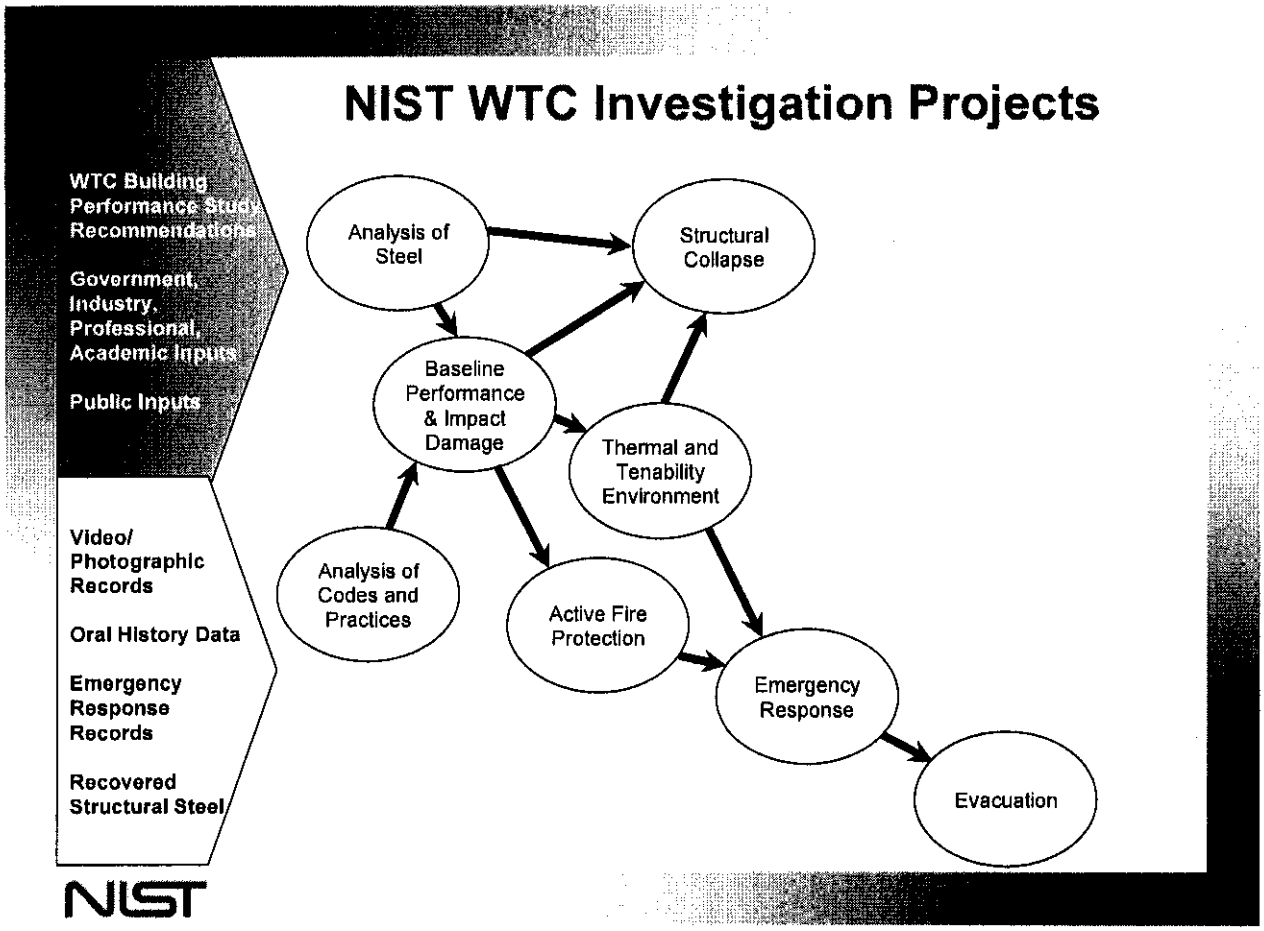

Figure P–1. The eight projects in the federal building and fire safety investigation of the WTC disaster.

National Construction Safety Team Advisory Committee

The NIST Director also established an advisory committee as mandated under the National Construction Safety Team Act. The initial members of the committee were appointed following a public solicitation. These were:

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